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DESIGN & ANALYSIS VORTEX TUBE REFRIGERATION SYSTEM

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ABSTRACT

A vortex tube works as a splitter of compressed gas stream bifurcating it into a hot and a cold stream without putting into use any chemical reaction or any external source of energy. This work focuses on variable geometries at the "hot end side" which are subjected to variable inlet parameters and the outcome of such an experiment is discussed. Hot end plugs have been employed to achieve the results. Three vortex tubes were designed, fabricated and tested for maximum temperature drop.

A detailed experimental analysis has been worked upon to detail out the behaviour of the vortex tube. A suitably designed test rig has been helpful in investigating the role of geometrical parameters such as the angle of the inline conical valve, tip diameter of the inline conical valve.

KEYWORDS: Variable Geometries, Maximum Temperature Drop, Geometrical Parameters, Inline Conical Valve & Tip Diameter

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Original Article

1. INTRODUCTION

Figure 1 displays the operational principle of the vortex tube. The tube operates by accepting the compressible fluid tangentially via the nozzles. On account of the cylindrical structure of the tube along with the inlet pressure and speed it leads to an internal circular movement that too at a high speed. With pressure difference between tube wall and the centre due the friction of the wall leads to transfer of energy from the centre region to the tube wall. The confined liquid which has cooled now moves against the major flow direction. The cooled fluid leaves the tube by moving against the main flow direction and the heated up fluid leaves in the direction of the major flow. The RHVT has been popularly employed for both cooling as well as heating purpose.

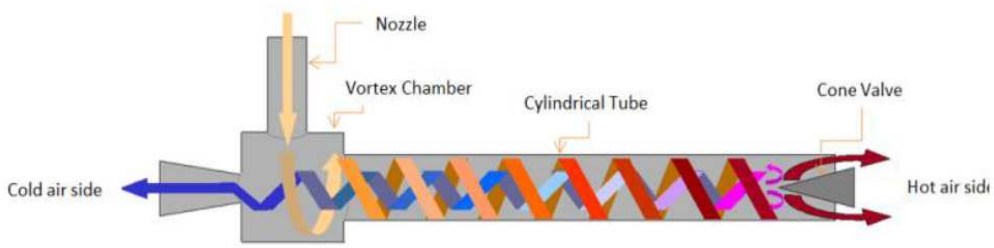

Figure 1: Schematic Diagram of Vortex Tube.

1.1 Nomenclature

Nomenclature		
Cp	Specific Heat of air	Kj/KgK
M	Mass Flow Rate	Kg/Sec
T	Temperature	°C
ΔT	Temperature Difference	°C
Tc'	Static Temperature Drop	°C
ΔT_{rel}	Relative Temperature Drop	°C
μ	Cold Mass Fraction	
Q	Cooling or Heating Rate	Kj/sec
V	Velocity	m/sec
W	Actual work done by the Compressor	Kw
ηad	Adiabatic Efficiency of Vortex Tube	%
Subscript		
i	Inlet to vortex Tube	
h	Hot air exit	
c	Cold air exit	

The vortex tube is a device which employs no devices which need to make some motion to operate and is capable of generating hot and cold air stream from its two ends using the compressed air. Lots of research has been carried out to understand the heat dynamics of a vortex tube with reference to the parameters like the cross section area of cold and hot end, nozzle area of inlet compressed air, cold orifice area, hot end area of the tube, and L/D ratio. It has been observed that the investigation carried out fails to present the perfect picture and hence physical verification has been carried to come a defining conclusion.

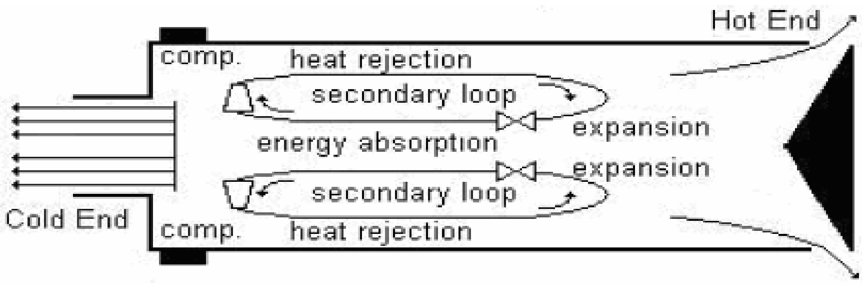

Figure 2: Energy Transfer Mechanism in Vortex Tube.

The vortex tube was invented quite by accident in 1928. George Ranque, a French physics accidently invented the vortex tube in 1928 while working to develop some pump where he noticed an exhaust of cool air from one end and hot air from another.

A. M. Dalavi, Mahesh Jadhav and Yasin Shaikh [1] worked upon investigation of heat transfer characteristics for parameters like cross section area of cold and hot end, nozzle area of inlet compressed air, cold orifice area, hot end area of the tube, and L/D ratio.

Ratnesh Sahu and Rohit Bhadoria[2] have been able to demonstrate experimentally the performance analysis of the vortex tube and optimizing the operational efficiency when put to use for industrial applications like spot cooling , weld cooling etc.

Akash S. Bidwaik and Sumit Mukund Dhavale [3] have worked upon a double inlet vortex tube with dc = 5,6, and 7 mm and eight tangential nozzles having L/D =11.5. This resulted in increased intensity of swirl. The governing equation for the same were obtained using ANSYS FLUENT 15.0 on a 3D model for fluid domain.

Jaykumar D. Golhar and B. R. Rathod [4] have experimented with the nozzle diameter and have been able to state that the nozzle diameter influences the performance and cooling efficiency and have been able to identify that the nozzle diameter can be optimized to give the best performance.

Kiran D. Devade and Ashok Pise [5] have parametrically reviewed the effects of around parameters which define the performance of the vortex tube with a focus on reviewing works carried on in order to enhance the refrigeration effect.

2. DESIGN METHOD

As far as the design is concerned the vortex tube can be fabricated in two ways with the first variant being the maximum temperature drop design for generating air with very low temperature and the other variant being the maximum cooling effect design for large quantity of air with moderate temperature. These designs have been employed to maximize the heat transfer rate during the forward motion of swirl air and reversed flow of axial air.

The basic design parameters for the vortex tube are

These two design considerations have been used in study for increasing the heat transfer rate during forward motion for swirl air and reversed flow of axial air. Designing criteria of the vortex tube is based upon the following condition:

- Ambient pressure (Pa)
- Inlet pressure (Pi)
- Inlet temperature (Ti)
- Cooling temperature (Tc)
- Temperature of hot body (Th)

For the conditions above vortex tubes can be designed with reference to the below mentioned parameters:

- Diameter of hot tube (DT)
- Length of hot tube (L)
- Cold orifice diameter (DC)
- Nozzle diameter (DN)

The existing literature identifies that for achieving a high temperature drop the nozzle design comes quite handy as compared to the cold orifice design and the cold fraction along with the adiabatic efficiency have a prominent role to play for the size of the cold orifice than the size of the nozzle. The literature also points out that the maximum temperature drop design results in higher temperature drop where as the maximum cooling effect tube design leads to more cold fraction and higher adiabatic efficiency. Another important observation in the literature is that the Length of the tube in the range of 45 to 55 (L/DT ratio) has no bearing on the performance of the tube.

The present study has been focussed on maximum temperature drop design for generating air with very low temperature. Considering Soni and Thomson the nozzle area to tube area ratio of 0.11+0.01 was setup for maximum temperature drop and a ratio of 0.084+0.001 for achieving maximum efficiency. Similarly as per their suggestion the ratio of cold orifice area to tube area should be 0.08+0.001 was fixed to maximize temperature drop and 0.145+0.035 for attaining maximum efficiency. The length e length of the vortex tube was set up to be 45 times greater than the tube diameter as per their suggestions.

The material utilized for cold end (inlet cap) is SS 304, and brass for the hot end to harness its excellent thermal conductivity while the remaining assembly is fabricated in stainless steel to keep a tab on the machining and the overall cost.

2.1 Designed Vortex Tube Apparatus

Figure 3: Final Designed Manufactured Vortex Tube.

The project is focused to check efficiency and application of the proposed apparatus when put to use in industry. The tube is used for instant cooling purpose, where we required dry coolant such that applications do not get damaged thus application where we need cooling for small application, we can use vortex tube. It is use in ultrasonic welds for cooling purpose. Cooling blow molded fuel tanks, and also use for spot cooling and use for cooling for turbine rotor blades

2.2 Operational Procedure

The experimentation is performed with counter flow vortex tube at different valve positions and varying pressures ranging from 7.2 to 8.3 bars. There are 7 valve positions from 0 to 100% opening at hot end side to restrict or release the hot mass of air. For every valve position the temperature rise and drop are recorded. So as to have a correct set of readings 03 measurements are recorded for every valve position and then the average temperature rise and drop are estimated respectively.

With the input fluid from the compressor which is the compressed air is passed through the pressure regulator to adjust the inlet pressure and then passed through the generator which is of brass material having 6 aero foil shaped cut due to which the air vortices are generated inside the vortex tube at very small vortex angle of 6 degrees. The rotation of generator and simultaneously the vortices work in direct proportion to the inlet pressure. The restrictor at the other end regulates the mass flow rate of the hot air to see its effect on temperature distribution at the ends of the vortex tube. The inlet and cold mass flow rate is measured with the help of anemometer, and the hot mass is calculated from mass conservation principle.

2.3 Analysis

Vortex tube performance is estimated by the following critical terms:

The ratio of mass of cold air to the mass air supplied is the cold mass fraction and is denoted by μ

$$\mu = mc/mi \quad (1)$$

where mc is the cold mass flow rate in kg/s and mi is the inlet mass flow rate in kg/s

Temperature drop at cold end is the temperature difference between inlet temperature and cold end temperature.

$$\Delta Tc = (Ti - Tc) \quad (2)$$

where Ti is the inlet temperature and Tc is the cold end temperature.

Temperature drop at hot end is the temperature difference between hot end temperature and inlet temperature.

Where Th is the temperature at hot end and Ti is the inlet temperature.

$$\Delta Th = (Th - Ti) \quad (3)$$

Cooling effect is the amount of cooling encountered at particular instance which is denoted by Qc.

$$Qc = mc\ Cp\ (Ti - Tc) \quad (4)$$

Heating effect is the amount of heating encountered at hot end at a particular instance which is denoted by Qh.

$$Qh = mhCp\ (Th - Ti) \quad (5)$$

Actual work done by the compressor can be estimated by the following relation,

$$W = (n/n-1) \times P1V1 \times [(P2/P1)^{(n-1/n)} - 1] \quad (6)$$

where P1 is the atmospheric pressure inlet to the compressor and P2isthe outlet gauge pressure.

Coefficient of performance is the ratio of cooling effect to actual work done by the compressor.

$$COP = Qc/W \quad (7)$$

Static temperature drop is the temperature drop due to adiabatic expansion which is represented by ΔTc.

$$\Delta Tc' = Ti - Tc' \quad (8)$$

where, Tc' = Ti[1- (Pa/Pi)(n-1/n)]

Relative temperature drop is the ratio of temperature drop in vortex tube to the static temperature drop which is denoted by ΔT_{rel}

$$\Delta T_{rel} = \Delta T_c / \Delta T_c' \quad (9)$$

Adiabatic efficiency is the ratio of actual cooling gained in vortex tube to the cooling possible with adiabatic expansion. It is denoted by ηad.

$$\eta ad = \mu \times \Delta T_{rel} \quad (10)$$

3. RESULTS AND DISCUSSIONS

3.1 Experimental

3.1.1 Effect of Inlet Pressure on Temperature Drop at Different Rotation of Valve Opening

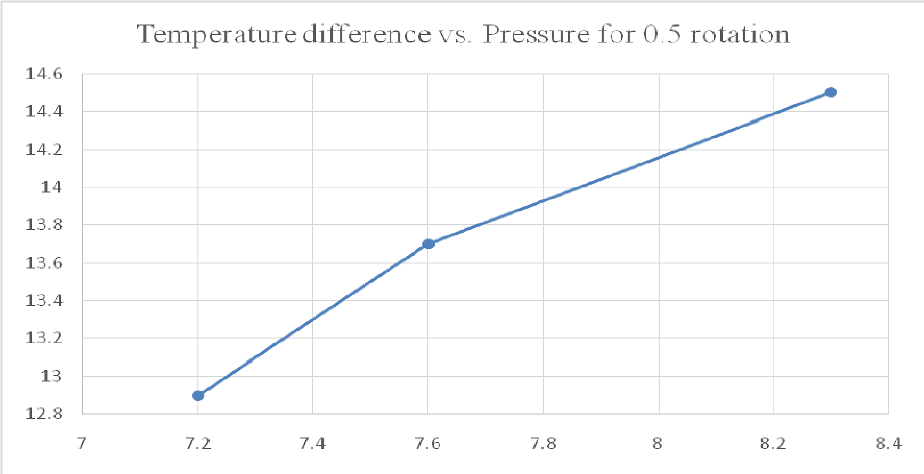

Figure 4

Figure 4 shows the effect of inlet pressure on ΔTc. The value of ΔTc increases with the increase in Pi for 0.5 rotation of valve opening with a straight line relation.

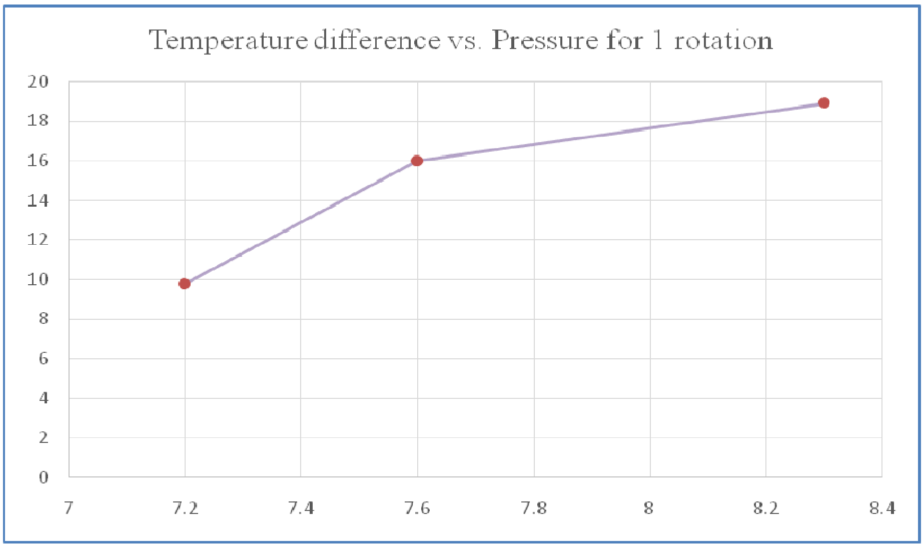

Figure 5

Figure 5 displays bearing of inlet pressure on ΔTc. The value of ΔTc increases with the increase in Pi for 1 rotation of valve opening with a straight line relation.

3.1.2 Effect of Rise in Pressure on COP at different Valve Openings

Figure displays the bearing of rise in pressure on COP at different location of valve opening. We can make an observation that the COP follows a direct proposition with pressure. It follows a straight line relationship which clearly shows the impact of pressure in producing cooling effect.

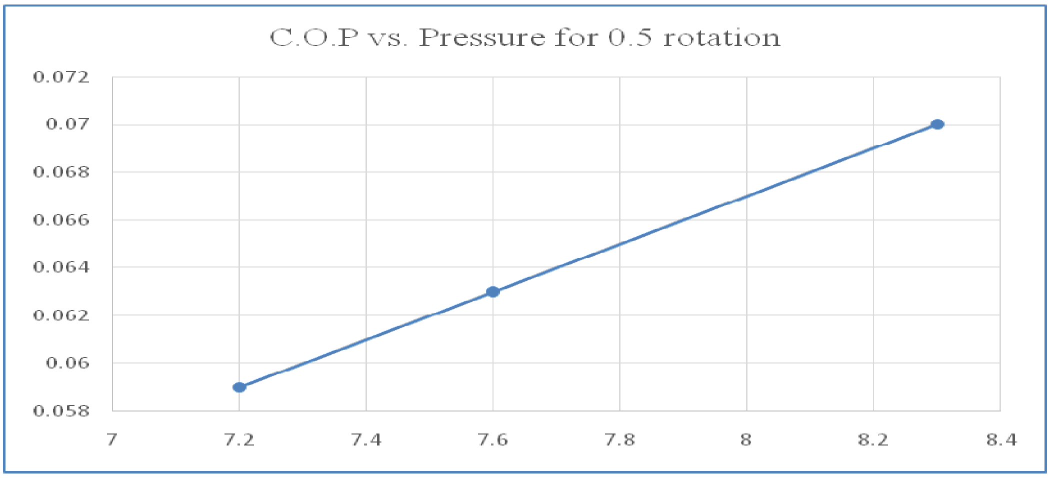

Figure 6

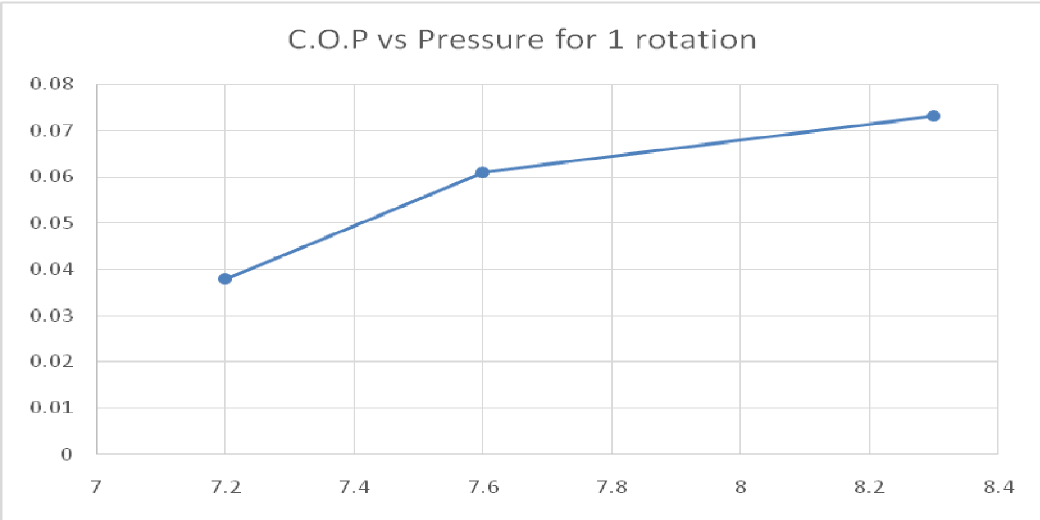

Figure 7

4. CONCLUSIONS

4.1 Effect of Humidity

For dryers not being put in service each of the compressed air system would be swamped by condensed water. For a vortex tube does there is no distinction between the humidity of the hot as well as the cold air and the absolute humidity of the of the hot as well as the cold air is similar to the compressed air. This results in moisture getting condensed or moved in a freeze state for a dew point higher than its temperature.

If moisture being precipitated in the air results in rise of the temperature of the cool air by approximately 3° to 4°every precipitated grain of moisture. This happens due to sensible refrigeration used up in producing latent refrigeration of the moisture. This refrigeration refigures out in the cool air as it warms up on exiting the vortex tube. On account of precipitation the moisture re-evaporates. From the table we can make an observation that condensation does not figures out for moderate cold end temperatures while low temperature results in snow formation.

This snow which is sticky in nature on account of oil vapours accumulates and hinders the cold air passage. To avoid such a situation there is a need to remove the condensed water from air and this can be achieved by employing a

filter separator. For an efficient performance the filter separator need to be placed in a close proximity to the vortex tube. Air can be used in the inlet line. The dryer employed should have a capacity to ensure that it generates an atmospheric dew point lower than the lowest expected cold outlet temperature.

4.2 Effect of Inlet Pressure and Back Pressure

Temperature drops and flows work in direct proposition to inlet pressure. The performance of the vortex tube suffers on account of the back pressure on the cold air exhaust. For Low back pressure, up to 2 PSIG (0.1bar), does not effects the performance but for pressure to tune of 5 PSIG (0.3bar) changes the performance by around 5° F (2.8°C).

4.3 Effect of Oil and Dirt (Filtration)

On account of moisture being resident in the compressed air lines of the tube they tend to be infested with rust and dirt. The filter separator helps in removing the rust and the dirt. It is elementary for the user to identify the frequency at which the filter would need a replacement. It is desired that the air used is clean and it recommended to use a filter having a filtration capacity of 25 microns or less and also contains a five micron element for which is properly sized to maintain the flow The use of clean air is essential, and filtration of 25 microns or less is recommended. A filter contains a five micron element and is properly sized for flow.

4.4 Effect of Inlet Air Temperature

A Vortex tube has the capacity to drop the air temperature from the temperature when the air was accepted in. A high input temperatures will result in a corresponding rise in cold air temperatures. The temperature drops or gains are proportional to the inlet temperature.

4.5 Effect of the Valve

During testing two different types of valves were used viz.

- Needle Valve (Bolt Type)
- Inline Conical Valve

It was observed that the Inline conical valve gave the maximum temperature drop. Thus this valve was recommended for further performance testing of the Vortex tube.

4.6 Nozzle used for the Vortex Tube

The nozzle used is altogether different than the one that was used by Prof. Parulekar in his short vortex tube. External U-threads were used for the tangential entry. The air attains the path followed by the threads with small helix angle and this helps producing the free vortex which after facing the restriction in the flow (Hot end control valve), becomes the forced vortex traveling in opposite direction with same angular velocity corresponding to sonic linear velocity.

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